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Final Report

# A Comparison of Lyman α and HeI λ10830 Line Structure and Variations in Early-Type Star Atmospheres

NGR 33-219-002

Submitted by

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and

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to

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NASA Headquarters

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## Introduction

The profile behavior and form of light element resonance lines such as HI Lyman α, HeI 10830 Å, OI 1302-6 and OI 7774/8446 provide important diagnostic information concerning the atmospheric structure of early-type stars. Because Lyα and 10830 occur in widely separated spectral regions, the constraints upon model atmosphere calculations these two lines provide are more severe than usually available, particularly when non-LTE effects are included. With this end in mind, the Vaughn pressure-scanned Fabry-Perot interferometer was modified for use as a narrow-band, single-order, near-infrared scanner. The modified device has been used on the 0.6 m telescope at the University of Rochester, C.E.K. Mees Observatory and most recently on the Kitt Peak National Observatory 0.9 m telescopes. The Copernicus Space Telescope of The Princeton University Observatory has been used to obtain Lyα as well as OI 1302-6 profiles in a number of stars in the 10830 observing program. In addition to the interest in the 10830 Å line as an indicator of stellar non-LTE conditions, the recently discovered correlation between solar 10830 Å emission and the lack of solar coronal X-ray emission (coronal holes) has sparked renewed discussion of resonance line formation mechanisms in turbulent regimes.

Starting in September 1977, the principal investigator will be spending a one-year sabbatical at the Goddard Space Flight Center as a NRC-NAS Senior Research Associate. During this time, effort will be concentrated upon final 10830 and UV line profile reductions, qualitative interpretations, and an initial start on quantitative aspects of an eventual model atmosphere analysis.

The Observational Programs - Current Status

To date approximately 80 scans of 10830 have been obtained in 50 "northern" OBA stars with a photometric accuracy of between 3% and 10% depending on the apparent infrared magnitudes of the stars. A wide variety of objects have now been surveyed between O5-A2 in spectral type and I-V in luminosity class. In addition to normal standard stars, particular attention has been paid to stars likely to show time-variations including

(a) Supergiants
(b) Be and Shell stars
(c) Bp and Ap stars
(d) Eclipsing and spectroscopic binaries.

Although the early 10830 observations were plagued by weather and instrumentation problems, since moving the instrumentation to Kitt Peak satisfactory results have been obtained. While the FW-118 sensitivity is not as high as when Vaughn used it, storage in the dry Arizona climate has produced an unexpected ten-fold reduction in the tube noise level. It was therefore possible to attempt moderate precision (3-5% counting accuracy) surveys of a number of stars not a part of the originally proposed program.

Some exploratory work on the HI Paschen 10938 and OI 7774/8443 lines has also been performed using the F-P interferometer. Limited wide-band narrow-band interference filter photometry of 10830 and 10938 has been obtained for a limited number of the brighter program stars. A photographic survey of the OI 7774/8443 lines in the program stars of later spectral types (B3-A5) and using I-N hypersensitized plates is continuing with the C.E.K. Mees 0.6 m telescope (University of Rochester). When the initial photographic survey is complete, observing time to obtain high accuracy Fabry-Perot profiles will be requested, probably at Kitt Peak.

As a summary of the current status of the observation program, Table I lists (according to right ascension) all stars for which raw F-P scans have been obtained with notes concerning the availability of Copernicus telescope UV scans. For stars for which Copernicus scans are either poor or not available, a comment in square brackets is given. Copernicus time for γ Ori, 13 Mon, o Pup, β UMa, and α CrB during late 1977 and 1978 is being requested.

In Table II, the stars presented in Table I are rearranged by special interest group. Those stars on the original observational list are indicated in Table II by a single asterisk. Of the original stars only three stars do not have satisfactory 10830 profiles available--α Col, σ Sco, and γ Peg. This is counterbalanced by the fact that twenty-four additional stars were obtained. Unfortunately, because of the instrumentation problems to be discussed later, the profiles deconvolution has become a more time-consuming task than originally envisioned and so even "quick-look" reductions are available only for about 30% of the stars listed.

## Instrumentation - Current Status

In spite of early instrumentation setbacks, it has now become almost routine to obtain raw F-P profiles at 10830 Å. Our original goal of real-time data reduction, however, was not realized. In particular, the use of $CO_2$ as the scanning gas introduces reduction complications of non-linear scanning intervals as well as zero point drifts due to $CO_2$ condensation in the F-P chamber. Instrumental modifications which will alleviate the $CO_2$ condensation problem are currently being incorporated into the F-P design.

## Table I

Right Ascension List of Stars for Which 10830 Profiles Have Been Obtained Using the Vaughn Fabry-Perot Interferometer (by June 1977) under NASA Grant NGR 33-219-002.

| | | | | |
|---|---|---|---|---|
| α And | B9p (Mn) | 1 scan | SB, φ = .96 | Copernicus Star |
| γ Cas | B0IV:e | 2 scans | | Copernicus Star |
| φ Per | B0ne: shell | 1 scan | SB, φ = .23 | Copernicus Star |
| β Per | B8V | 6 scans | EB, φ = various | Copernicus Star |
| ψ Per | B5ne: shell | 1 scan | | Copernicus Star |
| η Tau | B7III | 1 scan | | Copernicus Star |
| ζ Per | B1Iab | 1 scan | | Copernicus Star |
| ε Aur | A8Ia/F0Iap | 1 scan | | [Too Faint for Copernicus] |
| β Ori | B8Ia | 3 scans | | Copernicus Star |
| γ Ori | B2III | 1 scan | | [No U2 scans?] |
| β Tau | B7III | 1 scan | | Copernicus Star (DDM) |
| λ Ori | 08, 0e5 | 1-1/2 scans | | Copernicus Star |
| θ Ori | 06 | 1 scan | | [Multiple, Poor Guiding] |
| ζ Tau | B2IVp (*) | 2 scans (φ = .74) | | Copernicus Star |
| δ Ori | 09.5III | 1 scan | | Copernicus Star |
| ι Ori | 09III | 1 scan | | Copernicus Star |
| ε Ori | B0Ia | 1-1/2 scans | | Copernicus Star |
| ζ Ori | 09.5Ia | 1-1/2 scans | | Copernicus Star |
| κ Ori | B0.5Ia (*) | 1-1/2 scans | | Copernicus Star |
| θ Aur | B9.5pv(Si) | 1 scan | | Copernicus Star |
| 17 Lep | Aeq (shell) | 1 scan | | [Too Faint for Copernicus?] |
| β CMa | B1II-III | 1-1/2 scans | | Copernicus Star |
| β Mon | B3Ve, B4V | 1 scan | | [Multiple, Poor Guiding] |
| 13 Mon | A0Ib | 1 scan | | [Copernicus Time Requested] |
| γ Gem | A0IV | 1 scan | | Copernicus Star (DDM) |
| α CMa A&B | A1V + wd | 1 scan | | Copernicus Star |
| ε CMa | B2II | 1 scan | | Copernicus Star |
| o² CMa | B3Ia | 1-1/2 scans | | Copernicus Star |
| η CMa | B5Ia | 1 scan | | Copernicus Star |
| β CMi | B7V (*) | 1 scan | | Copernicus Star (DDM) |
| o Pup | B0pe | 1 scan | | [Copernicus Time Requested] |
| α Leo | B7V | 2 scans | | Copernicus Star |
| η Leo | A0Ib | 1 scan | | [U2 selected lines] |

Table I (continued)

| | | | |
|---|---|---|---|
| β UMa | A1V | 1 scan | [Copernicus Time Requested] |
| ρ Leo | B1Ib | 1 scan | Copernicus Star |
| γ UMa | A0Vn | 1 scan | Copernicus Star (DDM) |
| γ Crv | B8III | 1 scan | Copernicus Star (DDM) |
| δ Crv | B9.5V | 1 scan | Copernicus Star (DDM) |
| κ Dra | B7Ve (*) | 1 scan | Copernicus Star |
| ε UMa | A0p (Cr) | 3 scans | Copernicus Star |
| $\alpha^2$ CVn | Ap | 2 scans | Copernicus Star |
| α Vir | B1V | 2 scans | Copernicus Star (DDM) |
| η UMa | B3V | 1 scan | Copernicus Star |
| β Lib | B8V | 1 scan | Copernicus Star |
| α CrB | A0V | 1 scan | [Copernicus Time Requested] |
| ζ Dra | B6III | 1 scan | Copernicus Star |
| α Lyr | A0V | 2 scans | Copernicus Star |
| P Cyg | B1e | 1 scan | Copernicus Star |
| δ Cyg | B9.5III | 1 scan | Copernicus Star (DDM) |
| α Cyg | A2Ia | 2 scans | Copernicus Star |

*Spectral classification may be incorrect.

Table II

F-P 10830 Stars Arranged According to Special Interest or Spectral Type Groups

**Supergiants**

| | | | | | |
|---|---|---|---|---|---|
| ζ Per | B1Iab | *κ Ori | B0.5Ia (**) | $o^2$ CMa | B3Ia |
| ε Aur | A8Ia/F0Iap | *ε Ori | B0Ia | η CMa | B5Ia |
| *β Ori | B8Ia | 13 Mon | A0Ib | η Leo | A0Ib |
| *ζ Ori | O9.5Ia | *α Cyg | A2Ib | ρ Leo | B1Ib |

**Early Be/Shell Stars**

| | | | |
|---|---|---|---|
| *γ Cas | B0IV:e | β Mon | B3V |
| φ Per | B0ne: shell | o Pup | B0pe |
| ψ Per | B5ne: shell | P Cyg | B1e |
| *ζ Tau | B2IVp (**) | | |

**Late B Peculiar Stars**

| | | | |
|---|---|---|---|
| *α And | B9p (Mn) | κ Dra | B7Ve (**) |
| θ Aur | B9.5p (Si) | *ε UMa | A0p (Cr) |
| 17 Lep | Aeq (shell) | $\alpha^2$ CVn | Ap |

**OB Stars**

| | | | | | |
|---|---|---|---|---|---|
| γ Ori | B2III | ι Ori | O9III | ε CMa | B2II |
| λ Ori | O8, Oe5 | *α Vir | B1V | | |
| θ Ori | O6 | η UMa | B3V | | |
| *δ Ori | O9.5III | *β CMa | B1II-III | | |

**Late B Stars**

| | | | | | |
|---|---|---|---|---|---|
| *β Per | B8V | *α CMa | A1V | *γ UMa | A0V |
| *η Tau | B7III | *β CMi | B7V (***) | *γ CrV | B8III |
| *β Tau | B7III | *α Leo | B7V | *δ CrV | B9.5V |
| *γ Gem | A0IV | β UMa | A1V | *β Lib | B8V |
| α CrB | A0V | *α Lyr | A0V | ζ Dra | B6III |
| | | | | *δ Cyg | B9.5III |

Notes:
* Original program star
** Classification in doubt or controversial
*** May be a Be star

These modifications should eliminate all zero-point drifts from future F-P 10830 observations. They, however, cannot alter the reduction problems already present in the data now on hand. The F-P is currently being stored at Kitt Peak in case additional observing time becomes available. No plans exist for use elsewhere as appropriate shipping funds are not available.

## Theoretical Analyses - Current Status

Initial modifications of computer codes of standard LTE model atmosphere programs for running on the University of Buffalo CYBER computer system have been made with the kind cooperation of Dr. H. van Horn of the University of Rochester and Dr. L. Auer of NCAR, Boulder, Colorado. Work on non-LTE problems will commence after LTE predictions have been generated.

## Future Goals and Aims

During 1977-78, the principal investigator will be a NAS-NRC research associate at the Goddard Space Flight Center where work on the available 10830 and Lyman α profiles will, hopefully, be completed. Therefore no follow-on proposal to this grant will be possible until the fall of 1978. Present plans call for semi-qualitative discussions of the available observational material to be published during 1977-78. The time-scale required before quantitative theoretical discussions can be attempted is difficult to predict, but 3-5 years is not unrealistic. Thus while the formal financial NASA support terminates with this report, work on the 10830 profile and related problems will continue. It seems appropriate to conclude this final report with a summary of intended future extensions of the grant work.

A. Observational Tasks (1977-80)

(a) During 1978-80 an effort will be made to complete the 10830 survey of all OBA stars up to $m_{IR} \simeq 3^{m}.5$ both northern and southern. NASA or NSF support will be solicited.

(b) During 1977-78, Copernicus UV observations will be proposed and hopefully completed using travel available as an NRC-Senior Associate. Observing proposals for guest-investigator status on the I.U.E. will be generated for the 1978-80 period.

(c) Completion of the photographic OI 7774/8443 survey will be attempted during 1977-78 by D. Kelly of SUNY-Geneseo. A photoelectric survey will be planned for 1978-80 once the results of the photographic survey are available.

B. Data Reduction and Publication

During 1977-78, final deconvolved F-P 10830 Å profiles will be constructed for all available data. It remains to be determined whether a single atlas or several specialized group atlases will be produced. Final UV profiles of Copernicus data will also be completed.

C. Theoretical Calculations and Model Atmospheres

In preparation for line profile calculations on the University of Buffalo CYBER system, the Computer Center staff of SUNY-Geneseo will modify as necessary several existing atmosphere programs including those made available by the University of Rochester and the Goddard Space Flight Center. By 1978, some non-LTE work may begin, either at Goddard or upon return to Geneseo.

Summary

The preliminary conclusions given in the AAS abstract accurately describe the present status of the work. Some additional details are given in the progress report dated January 1977. Time has not permitted generating a similar description here for the profiles obtained in March 1977. It can be stated, however, that the interactions of doppler-shifted 10830 Å components and the SiI 10827 Å appear to be real and represent a serious complication that was not previously suspected. Even when there is no apparent 10830/10827 interaction, profile changes on time scales short compared to the scan time are so serious that for some stars, it may be impossible to ever obtain a satisfactory final deconvolved contour. Although progress was much delayed by instrumentation difficulties, it is felt that the available 10830 raw data certainly satisfies the originally stated objectives of the ground-based part of the grant proposal. The concentration on the 10830 problem seemed obligatory and timely. Hence progress on the OI lines and the model atmosphere calculations was very limited. It is hoped that the NAS-NRC Senior Associateship will enable the principal investigator time to complete the data analysis as well as initiate several publications on the 10830 problem. In this sense, the 1977-78 period is envisioned as a period of "no-cost" extension of the present work. Copies of the publications produced while on the Goddard staff will be transmitted to NASA headquarters to be kept on file as appendices to this final report.

Publications Under This Grant

Meisel, D. D., Saunders, B. A., and Kelly, D. R. 1977, "Helium 10830 in Early-Type Stars," Bull. Am. Astron. Soc. 9, 366.

Feeney, M. T. 1976, "A Study of Lyα and OI λ1306 Line Profiles in Early Type Stars," M.A. Physics Thesis, SUNY-Geneseo.

Meisel, D. D. and Berg, R. A. 1975, "Helium λ10830 in Alpha Virginis A and B," Ap. J. 198, 551.

Meisel, D. D. and Berg, R. A. 1974, "High Resolution Spectrophotometry of Selected Features in the 1.1 μm Spectrum of Comet Kohoutek (1973f)," Icarus 23, 454.

The JSC/SRL features a 40-cm aplanatic reflector with a dual star-tracking system and a detector system consisting of an echelle spectrograph and an SEC Vidicon. The spectrum longward of about 2800Å exhibits numerous emission features attributable to the extended atmospheres of this late-type supergiant (M2 Iab). Of particular interest is the asymmetry in one of the Mg II resonance doublet emissions (2795.523 and 2802.698Å). As reported earlier (Kondo et al., 1972, Ap. J., 176, 153; Kondo, Morgan and Modisette, 1975, Ap. J., 196, L125; and Bernat and Lambert, 1976, Ap. J., 204, 830), the 2795 emission is asymmetric due to the selective absorption occurring in the cool shell surrounding Betelgeuse. Modisette, Nicholas and Kondo (1973, Ap. J., 186, 219) attributed the asymmetry to the selective absorption by Fe I (2795.006Å) while Bernat and Lambert attributed it to Mn I (2794.817Å) and Fe I. In the current results we are able to delineate the absorption due to the neutral metal as a distinct absorption feature rather than merely as asymmetry in the Mg II 2795 emission. The central wavelength of this absorption feature tends to favor Fe I.

33.08.05 Low excitation early-type emissions and late-type absorptions in the spectrum of RX Puppis M. KLUTZ, O. SIMONETTO, and J. P. SWINGS, Univ. Liège, Belgium. The high excitation emission lines typical of a true symbiotic star that were reported by P. Swings and Struve in 1941 are now absent. Spectrograms obtained in 1972, 1975, 1976 show essentially emission lines of H (with rapidly variable P Cygni structure) and permitted and forbidden emissions of singly ionized metals, mainly FeII. In addition sharp absorptions are detected in 1977 on 20 Å $mm^{-1}$ spectra that are now obtainable because of the increase in brightness of RX Puppis. An analysis of these new data will be presented.

33.09.05 Balmer Lines Near the Series Limit in A-Type Spectra. R. J. PANEK, Penn State U. For seven bright, A-type stars, the absolute flux at 3600-4200 Å has been measured with 10 Å resolution, using a photoelectric scanning spectrometer. An attempt was made to directly determine the instrumental line profile. The program stars are well suited to comparison with models because they have a well determined angular diameter and empirical effective temperature. The effective temperatures range from 8000-10000°K, and the surface gravity from log g = 3.5-4.5. New synthetic spectra in this wavelength interval have been computed using recently published, line blanketed model atmospheres. These calculations explicitly include the detailed line absorption profiles of thirty Balmer lines. The quasistatic approximation which is used for the Stark broadening should be accurate for these high series lines. The theoretical spectra were convolved with the instrumental profile for direct comparison with the observations. Each star is compared to a model on the basis of effective temperature. The model continuum fluxes for the hotter stars tend to be faint near 4000 Å. After allowance for the absorption of metal lines not included in the theoretical spectra, the converging Balmer lines are quantitatively seen to be well reproduced by these theoretical spectra.

33.10.05 Moderate Resolution Ultraviolet Rocket Observations 912-3100 Å of Seven Early-Type Stars. W. H. BRUNE, G. H. MOUNT, and P. D. FELDMAN, The Johns Hopkins University. - Ultraviolet spectra in the wavelength region 912 to 3100 Å of seven hot stars were obtained at 15 Å resolution with three scanning spectrometers. The spectrometers were aboard an Aerobee 170 rocket, which was launched from Australia on February 17, 1977, at 13:30 U.T. Stellar fluxes have been determined with high photometric accuracy. Stars observed were γ Vel (C 7), ζ Pup (O5), α Eri (B5 IV), β Cen (B1 II), α Vir (B1 V), α CMa (A1 V). The data will be presented and compared with the predictions of stellar model-atmosphere calculations. Possible detection of the white dwarf companion of Sirius will also be discussed. This work was supported by NASA under grant NGR 21-001-001.

33.11.05 Helium 10830 in Early-Type Stars I. D. D. Meisel,*† B. A. Saunders, and D. R. Kelly, SUNY-Geneseo. - Fabry-Perot interferometric profiles for fifty of the brighter early-type stars including supergiants, eclipsing binaries, Bp and Ap stars, Be and shell stars, and variable stars have been obtained using the Kitt Peak 0.9 m telescopes and the C.E.K. Mees 0.6 m telescope. Results for β Persei (Algol) just before primary and secondary eclipses show strong emission profiles lasting about 0.1 phase. An absorption line was seen during secondary eclipse. A sampling of bright supergiant stars (O9-A2) show time-variable, complicated absorption/emission profiles similar in many respects to those obtained for the Be/shell stars. Observations to complete at least one profile of all 5 stars brighter than $m_v$=4 north of δ=-25° will continue. Ultimately these

10830 profiles will be compared to Lyα and OI 1306 profiles in the same stars.

This work was supported by NASA Grant NGR 33-219-002.

*Associate C.E.K. Mees Observatory, University of Rochester.
†Visiting Astronomer Kitt Peak National Observatory, Operated by Associated Universities for Research in Astronomy and Guest Investigator, Copernicus Telescope, Princeton University Observatory.

33.12.05 The Infrared Eclipse of V444 Cygni and the Structure of Wolf-Rayet Stars. L. Hartmann, CfA - Observations of the eclipse of the WN5 component of the V444 Cyg system at 2.2 and 3.4μ confirm the idea that free-free emission is the source of the infrared excess. The optical and infrared eclipses have been investigated with a stellar atmospheres program; the results support the model of Hartmann and Cassinelli (1977, Ap. J., in press) of the WN5 star HD 50896, in which the optical photosphere is not accelerating. The uniqueness of the model is discussed, along with implications for theories of radiatively driven winds.

33.13.05 The absolute spectral energy distribution of η UMa (B3V) in the ultraviolet and the visual. G. J. STRONGYLIS, UNIV. OF MARYLAND and R. C. BOHLIN NASA/GSFC. The absolute spectral energy distribution of the star η UMa (B3V) has been observed in the ultraviolet with the OAO-2, TD1-S2/68 and Apollo 17 experiments, and by Bohlin and Stecher with rockets. This basic collection of observations shows a maximum scatter of 35% near 1500 Å. Longward of 1700 Å these data have a typical scatter of only ±5%. A new model atmosphere from Kurucz with $T_e$ = 17000 K and log g=4.00 agrees well with the collected ultraviolet observations and the visual flux distributions on the Hayes and Latham scale. The unreddened model is within 20% of all observations in the 1200 to 1700 Å region and within 5% longward of 1700 Å. A slightly modified version of the model that accounts for the line blocking observed by the Copernicus satellite is proposed as the absolute flux standard in the ultraviolet and the visual. This standard can be used for in-flight calibrations and to derive revised absolute calibrations for any experiment, thus placing all absolute flux measurements on a common scale. Near the peak of the interstellar extinction curve at 2160 Å there is a maximum of 5% difference between the model and the observations. In order to address the question of whether the rapid rotation of η UMa (v sin i=216 km $s^{-1}$) has a significant effect on the shape of the ultraviolet continuum, the TD1-S2/68 flux distributions of η UMa and the slow rotator ι Her (B3IV, v sin i=8 km $s^{-1}$) were compared in the 1400 to 2500 Å region. The observed differences in shape can be explained to 2% by a reasonable amount of extinction with E(B-V)=0.$^m$02, plus a small difference in temperature of ΔT=1400 K. Thus, the non-rotating model that fits best the observations of η UMa in the ultraviolet has an error in the proposed flux of less than 2%, attributable to rotational effects.

33.14.05 The Superposition of Layers Method Applied to Emitting Atmospheres. R. W. WHITAKER and H. G. HORAK, University of California, Los Alamos Scientific Laboratory. - The superposition of layers method is applied to plane-parallel atmospheres with given source distributions. The procedure is based on the direct application of the principles of invariance combined with required symmetry relations.* The method is discussed for source distributions that are polynomial or exponential functions of optical depth. Numerical results are presented.

*The Transfer of Radiation by an Emitting Atmosphere.

II. H. Horak and C. Lundquist, Ap. J. 119, 42, (1954).

IV. C. Lundquist and H. Horak, Ap. J. 121, 175, (1955).

## WEDNESDAY, 15 JUNE

### Session 34: Room 500, General Classroom Building

### 1400-1730

PS.01.03 Energetics of Newly Formed Coronal Loop Systems. G. W. PNEUMAN, NCAR. - Following solar flares and major coronal transient events, newly formed magnetic loops are often observed in x-rays, XUV lines, and in Hα. The loop system rises into the corona from the base at velocities of the order of 10 km/sec. This upward motion does not reflect the expansion of single loops but, rather, the formation of new loops at successively greater heights. According to the theory of Kopp and Pneuman, this phenomenon is the result of the reconnection of field lines previously torn open by the force of the transient event, i.e., the relaxation of the magnetic field to its original closed equilibrium configuration prior to the flare. One important observed property of these systems is that very high temperature material ($T \sim 7 \times 10^6$K) is seen at the top of the most recently formed loops - indicating a large energy input at this location. Since the closed loop geometry following reconnection possesses a lower energy content than that of the open geometry immediately following